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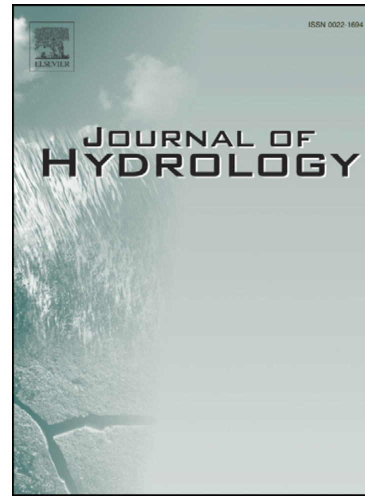

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Multi-decadal oscillations in the hydro-climate of the Okavango River system during the past and under a changing climate

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Abstract

The focus of this paper is to understand the multi-decadal oscillatory component of variability in the Okavango River system, in southwestern Africa, and its potential evolution through the 21st century under climate change scenarios. Statistical analyses and hydrological modelling are used to show that the observed multi-decadal wet and dry phases in the Okavango River and Delta result from multi-decadal oscillations in rainfall, which are likely to be related to processes of internal variability in the climate system, rather than external natural or anthropogenic forcing. Analyses of changes in

this aspect of variability under projected climate change scenarios are based on data from a multi-model ensemble of 19 General Circulation Models, which are used to drive hydrological models of the Okavango River and Delta. Projections for the 21st century indicate a progressive shift towards drier conditions attributed to the influence of increasing temperatures on water balance. It is, however, highly likely that multi-decadal oscillations, possibly of similar magnitude to that of 20th century, will be superimposed on the overall trend. These may periodically offset or amplify the mean drying trend. This effect should be accounted for in water and catchment management and climate change adaptation strategies.

1 Introduction

1.1 Background and study aims

The region of south-western Africa contains major rivers of international importance: the Okavango and the headwaters of the Zambezi and Congo rivers, and climate change projections for the 21st century indicate a shift towards a drier climate (IPCC, 2007). As such, and given the growing populations of basin states and their water demands, future regional hydrological processes are of particular concern. The Okavango River rises in the uplands of central Angola and drains an area of over 140,000 km^2 before terminating in an inland alluvial fan, the iconic Okavango Delta located in Botswana. The Delta is a 12000 km^2 endorheic wetland ecosystem (Fig. 1) and is an economically important hub of wildlife-based ecotourism. The entire Okavango basin is subject to persistent sequences of low and high flood years on multi-decadal time scales (30+ years), which are clearly evident from the observed hydrograph of the Okavango River (Fig. 1).

Understandably, transitions between decades of high and low flows impact the ecosystem and socio-economic activities in the area. It is, therefore, important to investigate whether similar oscillations will also be present in the future, particularly in the context of anthropogenic climate change. In this paper we i) undertake a comprehensive analysis of the nature and drivers of the observed hydrological multi-decadal oscillations; ii) evaluate the potential role of multi-decadal oscillations in the Okavango River basin in the 21st century as simulated by global climate models under anthropogenic climate change scenarios.

The results are discussed in the context of planning and development of climate change adaptation strategies for the Okavango basin, and in the general context of water management and natural resource management (in the broad sense) under conditions of changing climate.

1.2 Multi-decadal variability in the hydro-climate system

Hydrological variability, apart from that in tidal systems, is obviously driven by climate and weather variability, and moderated by properties of the catchment (e.g. Nemec and Schaake, 1982), including anthropogenic land use change and land-atmosphere feedbacks.

Multi-decadal oscillations in climate can occur as a result of i) stochasticity of climatic processes (Wigley and Raper, 1990), ii) interaction between the relatively slow reacting cryosphere, land and oceans, and the relatively quickly changing atmosphere (Mann and Park, 1994), enforced by thermohaline currents (Delworth and Mann, 2000), or the formation of cloud belts (Hunt and Davies, 1997) and iii) forcings external to the climate system, such as periodic changes in solar radiation (Waple et al., 2002).

Oscillations at time scales longer than 30 years have been detected in global rainfall (New et al., 2001), Mediterranean, eastern-USA and Eurasian climates (Enfield et al., 2001), Atlantic hurricanes (Zhang and Delworth, 2006) and regional rainfall, e.g., in the Sahel (Hulme, 1992), Brasil (Knight et al., 2006) and Australia (Power et al., 1999). Oscillations of 30-70 year period are also present in large-scale sea surface temperature (SST) patterns and are described by SST variability modes such as Interdecadal Pacific Oscillation (IPO, Power et al., 1999), Pacific Decadal Oscillation (PDO, Mantua et al., 1997) and Atlantic Multidecadal Oscillation (AMO, Kerr, 2000). Surface pressure fluctuations such as the North Atlantic Oscillation (NAO, Hurrell, 1995) also display a multi-decadal component. These SST/pressure variability modes have been linked either heuristically, or through physical processes, with the multi-decadal oscillations present in local, regional or global climates. Such linkages are, however, complex and affected by other factors. For example, decadal variability in Sahelian rainfall is related to the global SST patterns (Folland et al., 1986), including the AMO (Zhang and Delworth, 2006; Knight et al., 2006) but is also influenced by global warming (Held et al., 2005; Biasutti et al, 2008) and the IPO (Mohino et al., 2010), and additionally modified by land cover-rainfall feedbacks (Biasutti et al., 2008).

Although the reasons for multi-decadal climate oscillations are still not fully understood, and it is not certain whether all processes leading to them are well represented in General Circulation Models (GCMs), such oscillations are found in numerous unforced (i.e., not accounting for anthropogenic greenhouse gas (GHG) emissions) and coupled (i.e., simulating both atmosphere and oceans) GCMs (e.g., Zhang and Delworth, 2006; Knight et al., 2006).

1.3 Multiannual and multi-decadal hydro-climate oscillations in the Okavango basin and southwest Africa

Periodicities in the Okavango and Zambezi discharges and rainfall have been studied earlier using Fourier analysis, and quasi-periodic fluctuations with 16-18 and 60-80 year, as well as shorter (3-8 year) cycle lengths were revealed (Mazvimavi and Wolski, 2006; McCarthy et al., 2000). The 60-80 year quasi-periodicity detected in the Okavango that is of primary interest here is conceptually problematic, considering the 80-year long instrumental record (flow measurements started in 1934, rainfall measurements at Maun have been carried out since 1922). However, the persistence of oscillations in this band is corroborated by 60-120 year cycles found through stalagmite and tree ring paleoclimatic analyses by Tyson et al. (2002), who attributed them to solar variability associated with the Gleissberg cycle of around 80 years that is linked to high and low phases of the 11-year solar cycle. More recently, Jury (2010) analysed the relationship between Okavango River discharges and sea surface temperature variability, and found a weak, but statistically significant relationship between the NAO index and summer (January-April) Okavango discharges.

On the other hand, Hoerling et al. (2006) demonstrated that south-west African rainfall is related to SSTs in the Indian Ocean and suggest that the global warming-driven increase in these is responsible for the 1950-1999 rainfall decline in the

Okavango region, but give no explanation for the increase in rainfall (and Okavango River discharges) observed since circa 1996.

That the multi-decadal pattern in Okavango discharges is not attributable to geomorphologic or land use change factors is suggested by the fact that the adjacent Zambezi system originating primarily from north-west Zambia, has exhibited a similar dry-wet-dry multi-decadal sequence since the 1930s, in spite of being subject to a different land use transformation from the Angola-located Okavango (Andersson, 2006).

The presence of multi-decadal oscillations in the Okavango system in the context of climate change was recognized by Murray-Hudson et al. (2006), who addressed it by visualizing changes in the ecosystem separately for wet and dry multi-annual periods. The explicit assumption they made in assessing future conditions was that dry and wet sequences will also occur in the future, and only their overall mean “wetness” will be modified. Other assessments of climate change impacts in the Okavango (e.g. Hughes et al., 2011) are based on standard 30 year ‘time-slice’ approaches and therefore do not explicitly take multi-decadal oscillations, nor any potential future changes in this phenomenon, into account.

2 Data and methods

2.1 General approach

In order to explore the nature and drivers of the multi-decadal variability in the Okavango system we analyse the presence and strength of multi-decadal patterns in river discharges and in the basin’s climate (rainfall and temperature-derived potential evaporation, PET). We use a spectral analysis framework where we treat the observed variability as quasi-periodic in nature and investigate whether the observed pattern could have arisen by chance, considering that the processes analysed are expected to be autocorrelated. Furthermore, we perform a sensitivity study based on hydrological model simulations, in which we assess the relative role of rainfall and temperature-driven PET in generating multi-decadal oscillatory patterns in the hydrological responses.

Our second aim is to quantify multi-decadal oscillatory patterns under projected future climate. In order to take into account uncertainties involved in future climate projections we utilize a multi model ensemble (MME) of 19 GCMs. This approach considers the different GCM simulations to be equiprobable (Tebaldi and Knutti, 2007), and avoids selection of a particular solution/model purely based on data availability, or ultimately subjective indices of model performance. We use GCM MME climates to drive a hydrological model and obtain an ensemble of simulated hydrological responses. This forms the basis for comparison of future and past multi-decadal oscillations accounting for GCM uncertainties.

2.2 Observed data

Hydrological data from the Namibia and Botswana parts of the Okavango basin are of good quality and sufficient length for the purpose of this study. We have used a monthly river discharge record of the Okavango River at Mohembo (Q_{OKA}), located immediately upstream of the Okavango Delta (Fig. 1). This record covers the period 1934-2011 and is an integrated indicator of catchment water balance processes. To capture processes taking place within the Okavango Delta, we have used monthly river discharges of one of the terminal rivers, the Thamalakane at Maun (Q_{THA}, Fig. 1). This record covers the period 1968-2011.

The climate network for the Okavango catchment is sparse and virtually no data were collected during the period of the 1975-2002 civil war in Angola, and hydro-climatic monitoring networks are still not fully functional. Additionally, archival climate data are often available only from secondary sources with unknown histories. Rainfall and PET data in the Okavango catchment were collated during development of a hydrological model of the Okavango catchment (Hughes et al., 2006; Wilk et al., 2006). These data, hereafter named SPATSIM, comprise area-average values for 24 subcatchments of the Okavango basin, and cover the period of 1960-2002. However, only data for 1960s and early 1970s are based on observations; thereafter, the SPATSIM data are synthetic. The SPATSIM data are too short to be analysed for multi-decadal effects, but are used in this study as a reference data set for hydrological modelling.

In view of the lack of sufficiently long and coherent observational data, we have opted to rely on gridded data for the analyses of multi-decadal signals in climate. We have used monthly rainfall and minimum/maximum air temperature from the CRU TS 3.0 dataset (hereafter named CRU, Mitchell and Jones, 2005). These data are on a 0.5 degree spatial grid and for the Okavango region cover the period of 1930-2006. We have also used one of the longest and most reliable rainfall records in the region, that of Maun (19.98S, 23.42E, elevation 917m, WMO station code: 68032, Fig. 1), covering the period of 1922-2010.

For illustrating a relationship between oscillations in the Okavango and SST variability, we have used indices of the dominant global-scale multi-decadal modes of SST variability, the PDO and the NAO, available from www.esrl.noaa.gov.

2.3 Global Climate models (GCM) data

Data for the MME of 19 GCMs were obtained from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (http://www-pcmdi.llnl.gov). Description of the models and their CMIP3 IDs that we used here can be found online (PCMDI, 2007).

Monthly precipitation and temperature data were used from each model from (i) the climate of the 20th century experiments (20C3M) in which GCMs are driven with time-varying natural (solar irradiance and volcanic aerosols) and anthropogenic (greenhouse gas and aerosol) forcing; (ii) the SRES A2 greenhouse gas emission scenario experiment (Nakicenovic et al., 2000) corresponding roughly to the "business-as-usual" projections, and covering the period of 2001-2100. In order to account for the uncertainty associated with internal variability in the modelled climate system, where available we evaluate multiple runs of individual GCMs (which have the same forcing fields but different initial conditions) separately. In total, 40 GCM simulations of 1900-2100 climate were used in our analyses.

Typically in climate change impact studies the coarse resolution GCM data are downscaled to a space/time resolution more appropriate to impact models (in this case catchment hydrological models). However, to date there is no consistent downscaled dataset over the study region, which (i) incorporates the full range of uncertainty associated with the GCM MME; (ii) provides a full time-evolving record over the 1st century, necessary for the study of multi-decadal variability and iii) covers the entire region. Even forthcoming dynamical downscaling experiments such as CORDEX under IPCC AR5 (CORDEX, 2011) will provide data for 30-year time slices only.

Statistical downscaling using a method based on self-organizing maps (Hewitson and Crane, 2006) has been applied in southern Africa but these data are limited in extent because they are conditioned on a (sparse) observational record, and are only available for a limited number of GCMs. To overcome the spatial limitations of statistically downscaling sparse observations a satellite rainfall product was used to downscale 10 GCMs for the Okavango (Wolski, 2009). However, our recent work indicates that considerable biases are present in the satellite rainfall over the Okavango, which may introduce errors into the statistical downscaling results. Thus, using downscaled data in our study would introduce additional uncertainty related to the downscaling method and data sources, and also limit the number of GCMs for which data appropriate for our study are available. In this case, therefore, we drive our hydrological models directly with GCM climate outputs following a bias correction of each GCM field (section 2.3.1). We recognise that GCMs are unlikely to be able to represent the full spatial detail of rainfall over the basin. Nevertheless, this may not be a major limitation because (i) the region is characterized by a relatively smooth NE-SW rainfall gradient which is well reflected in the GCM rainfall fields (ii) the catchment hydrological model used runs at a coarse spatial sub-basin and monthly time scale. GCM data were used to run hydrological models (Section 2.4), which require fields of precipitation and potential evapotranspiration (PET). To this end we have calculated PET using the Hargreaves method (Hargreaves and Samani, 1985), as it is based solely on maximum and minimum monthly temperatures, and thus compatible with the available GCM data.

Biases present in GCM data limit their direct application in hydrological models (described in section 2.5), as this would result in running models under regimes different to those observed in reality, and present in the reference simulations. An unbiasing procedure was therefore implemented on each of the GCM run datasets, which in case of the catchment model involved the following steps:

(i) The climatological mean and variance of P and PET derived from SPATSIM dataset (1960-2002) were obtained for each of the sub-catchments;

(ii) Outputs of P and PET from individual GCM runs were interpolated from the native GCM resolution to a 0.5 degree grid and subsequently area-average values were derived for each of the sub-catchments;

(iii) The P and PET time series (1900-2100) for each GCM ensemble member for each sub-catchment were converted to monthly anomalies with respect to the climatological means for the 1960-2002 period;

(iv) These anomalies were then scaled to ensure equal variance with the SPATSIM anomaly time series, by multiplying by the ratio of SPATSIM and GCM variances;

(v) The resulting bias-corrected anomaly time series was then added to the SPATSIM monthly climatological mean.

An analogous procedure was implemented for the model of the Okavango Delta. The results of this unbiasing procedure were monthly time series of rainfall and PET for each of the models' units for 1900-2100. These series had the same monthly means and variances in the 1960-2002 period as the data originally used in the models, but maintained the interannual and multi-decadal variability patterns of the original GCM data.

2.4 Time series analysis techniques

For illustration purposes we present time series of monthly quantities filtered using a 30-year running average. In all plots the running average is shown for the 30 years preceding the particular year (not centred on that year).

To analyse the presence and strength of multi-decadal oscillations in climate and hydrological record in the Okavango we utilized the multi-taper method (MTM) of spectral analysis (Ghil et al., 2002). Unlike classical Fourier analysis, which detects signals of fixed amplitude and frequency, this method permits the detection of the amplitude and phase modulations of a range of periodicities centred on given frequency bands. The MTM also provides a quantitative description of significance of both quasi-periodic and periodic variability in relation to the background (autocorrelated) red noise, which is robustly estimated from the data (Mann and Lees, 1996). For the analyses of oscillations observed in the past, MTM was used on data series for 1934-2006, the time span selected to match the available observed Okavango River discharges and CRU data series.

2.5 Hydrological models

In this study, we use hydrological models for two tasks: (i) in the framework of a sensitivity analysis aiming at determination of the relative roles of rainfall and temperature-driven PET in generating the multi-decadal oscillations in Okavango and Thamalakane River flows and (ii) in the framework of MME analysis to assess the future multi-decadal oscillations in hydrological conditions in the Okavango River and Delta under ensemble GCM climate projections.

The hydrological model of the Okavango catchment described by Hughes et al. (2006) was used in our study without any structural modification or recalibration. The model is a semi-conceptual semi-distributed monthly rainfall-runoff model known as the Pitman model. The input to the model consists of rainfall and PET time series for 24 sub-catchments of the Okavango basin upstream from Mohembo on Botswana border. The model simulates surface and groundwater runoff and routing through the channel network, and generates river discharges at the catchment outlet, i.e. at Mohembo. This model output is fed into a second, semi-conceptual semi-distributed model of the Okavango Delta that simulates inundation in large units of the Okavango wetland system as well as outflows though terminal rivers including the Thamalakane (Wolski et al., 2006).

The models have been run with CRU and MME GCM-derived data. The CRU dataset differs from the original data sets developed for calibration of the hydrological models, and when applied to these models, differences arise between observed and simulated discharges. These differences are particularly strong for several individual years and cannot be reduced by model recalibration, an effect also noted by Hughes et al. (2011). The seasonal pattern and long-term mean catchment discharge are, however, relatively well represented (the latter within 10% of observations). Since we are concerned with long-term variability, we have decided to use the models without recalibration.

The hydrological models of the Okavango catchment and Delta have been run with various combinations of original and modified CRU data where frequencies with period longer than 30 years were filtered out. The filtered series of rainfall and temperature were obtained from CRU data by using a simple low pass Fourier filter.

Four scenarios were simulated:

(i) run 1: unmodified rainfall and unmodified PET

(ii) run 2: filtered rainfall and unmodified PET

(iii) run 3: filtered PET and unmodified rainfall

(iv) run 4: filtered rainfall and filtered PET

This relatively complex sensitivity analysis was undertaken as simpler methods, such as multiple regression, could not be used to resolve the relative importance of rainfall and PET in determining the oscillations of river discharges.

For analyses of hydrological conditions under future projected climates the hydrological models were run with inputs derived from each of the 40 GCM simulations.

3 Results

3.1 Past hydro-climatic oscillations

Here we address the first of the two aims of this paper, to analyse the nature and drivers of climatic and hydrological oscillations at the multi-decadal timescales.

3.1.1 Running averages and their ranges

When smoothed with a 30-year running average to retain multi-decadal features, all analysed variables, P_{MAUN}, P_{CRU}, PET_{CRU}, Q_{OKA} and Q_{THA}, show a clear and essentially similar temporal pattern of multi-decadal oscillations (Fig. 2). For P and Q minima occur in the 1950s and early 2000s, and a maximum in the 1980s while for PET this pattern is reversed (high-low-high).

The peak-to-trough range of the 30-year running mean is larger in the P_{MAUN} time series than in that of P_{CRU} for all three zones (Table 1), which may reflect areal smoothing or underestimation of multi-decadal oscillations in the CRU dataset. The Q_{OKA} run1, which is driven by unfiltered P_{CRU} and PET_{CRU}, exhibits dampened fluctuations (peak-to-trough range of only 18% of mean) relative to the observed (28% of mean). This may be due to misrepresentation by the model of slow hydrological processes in the catchment, but is more likely to result from underestimation of the multi-decadal signal in the P_{CRU} series. Importantly, the peak-to-trough ranges for P_{CRU} are significantly larger than those for PET_{CRU}. Also, there is a gradual downstream increase in the role of multi-decadal fluctuations in the hydro-climatic variables: while inputs – P_{CRU} and PET_{CRU} – exhibit peak-to-trough range in the order of 2-3.5% and 8-15% of the long-term mean respectively, simulated Okavango discharges have the range of 18%, while the observed discharges - 28%. For the location furthest towards downstream, the Thamalakane, the peak-to-trough range of simulated discharges reaches 108 %, while for the observed discharges it is 79% (Table 1).

3.1.2 MTM spectra

Broadly, the MTM spectra of the analysed variables reveal the existence of a multi-decadal component (Fig. 3 and 4). The MTM spectrum of Q_{OKA} is dominated by a signal at ~30 years and beyond, and at shorter frequencies of ~7 years. The >30 years signal is very strong in PET_{CRU}, although considerably weaker in P_{CRU}. The spectrum of Okavango River discharges simulated with CRU data does not closely resemble that of observed discharges (compare Q_{OKA} obs and Q_{OKA} run1 in Fig. 4) with weaker power in the decadal bands. It is, however, similar to the MTM spectrum of P_{CRU} in zone 3 (compare Q_{OKA} run 1 in Fig. 4 and P_{CRU} zone 3 in Fig. 3). That rainfall variability in zone 3 dominates the modelled response of the entire catchment is not unexpected: the mean annual rainfall is the highest in zone 3 (Table 1), and most of the runoff is generated there. Importantly, the MTM spectrum of PET_{CRU} with a strong multi-decadal signal does not seem to be reflected in the modelled catchment runoff. MTM spectra for observed (Q_{THA} obs) and modelled Thamalakane River discharges (Q_{THA} run1) essentially replicate the respective Okavango discharges, but the strength of the long-term signal (>30 years) is amplified relative to the short term one (<30 years).

Out of the analysed variables, only PET_{CRU} data show oscillations in the multidecadal band that are statistically significant at 0.1 confidence level (Fig. 3 and 4).

3.1.3 Sensitivity of hydrological responses to multi-decadal signal in P and PET

The results of modelling with synthetic (filtered) inputs (Fig. 4, Table 1) show that the multi-decadal signal is present in river discharges in simulations with unmodified rainfall series (run 1 and run 3), regardless of whether or not the PET series contains such a signal. On the other hand, the multi-decadal signal is considerably weaker in the simulation with unmodified PET and modified rainfall (run 2), This clearly indicates that the multi-decadal signal in river discharges is more strongly related to that in rainfall than in PET.

3.2 Multi-decadal oscillations in GCM MME

Here, we address the second aim of the paper, to evaluate, based on the GCM MME, the simulated multi-decadal oscillations in the Okavango River basin in the 21st century in comparison to those in the 20th century.

3.2.1 Projections of rainfall and PET

30-year running averages of GCM rainfall (Fig. 5) and PET display different long-term patterns. PET, driven by temperature, is characterized by a slow rise throughout the 20th century, and the rise accelerates over the 21st century. That trend dominates the longer-term variability of PET, so that only a very weak signature of multi-decadal oscillations is present in the 21st century. There is considerable similarity between the various GCMs, and also, differences between the three zones are minor (not shown).

For rainfall, the various MME members differ considerably in terms of long-term patterns (Fig. 5 and Fig. 6). While most of the MME members show multi-decadal oscillations (Fig. 6), these are often superimposed on overall trend-like patterns. Some members (e.g. PCM) do not show any strong change in rainfall throughout the 21st century, while others (e.g. CGCM3.1(T63)) show an overall increase of rainfall. Approximately 20 members (11 different GCMs) project an overall downward trend in rainfall in the 21st century, indicating the high degree of uncertainty in GCM projections of rainfall noted in previous studies (Andersson et al., 2006; Wolski et al., 2006; Hughes et al., 2011). This uncertainty increases towards the end of the 21st century, which is expressed by the widening of the MME envelope (Fig. 5).

Since the distribution of the analysed signal is mono-modal (at 90% significance level, tested with dip test, Hartigan and Hartigan, 1985), the median of the MME effectively indicates the central tendency of the entire ensemble. The median does not show any significant trend in the 21st century rainfall (Fig. 5).

As indicated by the medians which do not show any pronounced oscillations, there is no agreement between members of MME in terms of the phase of oscillations in rainfall and PET in the 20th century. There is also no agreement in the phase of 21st century oscillations. We therefore conclude that the oscillations present in individual MME members, and thus in observations, are unlikely to be associated with anthropogenic or solar forcings (which are identical across the MME) and rather are due to internal variability in the ocean-land-atmosphere system.

3.2.2 MME projections of Okavango and Thamalakane River discharges

The general pattern of the MME is that of an overall reduction in Okavango River discharges in the 21st century (Fig. 7 and Fig. 8). The individual members, however, differ. For some members there is considerable variability superimposed on the long-term downward trend (e.g. IPSL-CM4), while for others, there is just a steady gradual decline (e.g. MIROC3.2(m) r2). There are also a few members that give an increase in discharges in the 21st century (e.g. CCSM r1) associated with dramatic changes/variability in rainfall (Fig. 5). There are also members that do not indicate any obvious trend in the Okavango River discharges during the 21st century while maintaining decadal and multi-decadal scale variability similar to that for the 20th century (e.g. PCM or CGCM3.1(T63) r2). For the Thamalakane River at Maun the overall pattern of MME is that of a reduction in discharges (Fig. 8). There are essentially no members showing increase of discharges compared to the 20th century. This is not surprising as the Thamalakane collects "spillover" from the Okavango Delta and thus its responses are strongly affected by evaporation, which is unequivocally projected to increase. Importantly, multidecadal oscillations in the discharges of the Thamalakane in the 21st century are evident in individual simulations shown in Fig. 8. Similarly to rainfall and PET, medians of MME for the Okavango and Thamalakane discharges do not display multidecadal oscillations indicating that there is no agreement between the members of the MME in phase of of such oscillations.

In order to determine whether the magnitude of the multi-decadal oscillations will change in the future, we have calculated the MTM spectral power associated with 30-60 year periodicities in the MME Okavango River flows for both 20th and 21st centuries (Fig. 9). Power spectra were calculated from detrended data to remove the influence of the overall trend on the broad-band spectra. The spectral power of GCM-based 21st century oscillations in MME appears to be similar to that of the 20th century (Fig. 9).

4 Discussion and conclusions

Within this paper we seek to understand the role of multi-decadal oscillations in the Okavango and the implications for planning and management of this system. We have addressed two research questions (i) what are the nature and drivers of hydrological oscillations at the multi-decadal timescales? ii) How will these oscillations be manifested under a changing climate?

4.1 Nature and drivers of multi-decadal oscillations in the Okavango system

Oscillations in the Okavango and Thamalakane River discharges are clearly driven by oscillations in rainfall and temperature-driven PET (Fig. 2). However, we find that the observed multi-decadal oscillations of the 20th century Okavango River discharges result primarily from the multi-decadal component in rainfall with little influence of that in PET. This is probably a result of the higher absolute magnitude of low frequency oscillations in rainfall (absolute range of 30-year averages of ~80 mm yr^{-1}) compared to that of PET (absolute range of 30-year averages of ~30 mm yr^{-1}), despite a statistically less significant signal in the former.

MTM-based tests for significance of oscillations in the time series indicate that only for PET_{CRU}, the observed multidecadal effects are stronger than those that may randomly arise from autocorrelation at shorter (annual) time scales. This suggests external forcing for that variable. The lack of significance of the multi-decadal oscillations in rainfall and river discharges in these tests does not imply that multi-decadal effects are not present. Rather, it indicates that the multidecadal effects are consistent with processes within the climate system (such as thermal inertia of oceans, or in the case of runoff, year-to-year carry-over storage) leading to autocorrelation at interannual and longer time-scales.

The evidence against the external forcing hypothesis for both rainfall and PET is provided by the patterns of multi-decadal oscillations in GCM MME (Fig. 5 and 6). Whilst we see pronounced multi-decadal oscillations in some MME members' rainfall and PET fields, the absence of a clear phase match with observations and between ensemble members implies internal climate mechanisms (particular to each GCM) as the drivers of these oscillations. For PET, this is somewhat contradictory to the results of MTM analysis. However, in view of the fact that the background red noise in MTM is actually estimated from the analysed series and thus may not reflect the strength of feedbacks driving the multi-decadal oscillations well, we consider the result of GCM MME analysis more likely. In summary, the results of our analyses point towards persistent internal feedbacks within the climate system as the primary source of the multi-decadal signal in the climate and hydrology of the Okavango system.

Understanding climate processes that may be potential drivers of these low frequency structures in the observed rainfall and temperature data is challenging on its own, and beyond the scope of this paper. Nevertheless, we note that the low frequency component of the analysed variables, i.e. rainfall, PET and river flows, is closely correlated with that of the NAO and PDO (Fig. 2e). The physical mechanism by which the NAO influences the southwestern African climate at these scales remains elusive but may relate to SST structures in the tropical Atlantic (Todd and Washington, 2004). Association with the PDO is strong but only at long lead times of many years. Clearly, we cannot draw any conclusions about what the drivers of multi-decadal variability may be, in this case.

4.2 Multi-decadal oscillations in the 21st century

A further aim of the paper was to assess the presence of and potential changes in multi-decadal oscillations in the Okavango system over the 21st century. This was addressed by the analysis of an ensemble of hydrological simulations based on data from an MME of GCM simulations for 20th and 21st centuries. A number of conclusions emerge. First, most members of the MME show pronounced multi-decadal oscillations in river discharges (Fig. 7 and Fig. 8), the magnitude of which does not seem to change in simulations of the future (Fig. 9). The individual MME members represent possible trajectories of the future hydro-climatic system. It is uncertain which of these trajectories the system will actually take. The MME median does not represent a more likely trajectory of river discharges, but rather indicates the central tendency of the entire ensemble.

Second, as implied by the multi-model ensemble median, our results indicate an overall downward trend in river discharges (Fig. 8). The decline is largely a reflection of increasing temperatures and consequently PET in both the catchment and in the Delta (Fig. 5).

The presence of significant multi-decadal oscillations in the 21st century has implications for the most common type of climate change assessment studies, which uses 30-year time slice averages to quantify climate changes. In analyses based on individual realizations of a single GCM, the effects of multi-decadal oscillations can be mistaken for a trend within such a period. In the ensemble of changes in the 30-year mean, whilst the ensemble mean is a robust estimate of the likely direction of change, the spread of simulated changes, which is generally interpreted as the uncertainty in projected mean changes, will actually include the effects of internal multi-decadal variability and so may lead to a wider range of estimated effects.

4.3 Implications for management of the Okavango system

The presence of multi-decadal oscillations in hydrological responses has rather important implications for the practice of water and environmental management in the Okavango system and elsewhere. This is because management (even in its new form applied to integrated water resources) is traditionally based on the assumption of stationarity of hydro-ecological systems. In this stationary model, a system oscillates around a “normal” state and a departure from this state is treated as an undesirable, and to a certain extent mitigable event, but importantly, the system is expected to return to its normal state shortly afterwards. Thus, management tools (such as policies and institutions) and development infrastructures (such as water supply systems) are optimized to suit that “normal” state and accommodate periodic departures. Should the departures be man-made, and considered undesirable, the system is to be returned to its “normal” state by rehabilitation, or possibly adaptive management actions. Such a philosophy underlies adaptive and integrated (catchment) management strategies (Ferrier and Jenkins, 2010). However, here we are describing a much more complex system, a system which does not return to “normal” after a periodic departure. Rather, it slowly shifts to oscillating around a slightly different “normal” state. For the Okavango Delta, the consequences of such transformations in the past have been dire. To give a few examples: the water supply system of the town of Maun, which could not supply enough water in the 1990s (because groundwater in the distal parts of the system was no longer recharged by the annual flood) was redesigned in the early 2000s, only to fail in 2008-2010 because large floods inundated the new wellfields. Furthermore, tourism and transport infrastructure, mostly designed and implemented in the 1990s, proved inadequate in the face of the large flooding of 2008-2010, and is currently being adapted to the new situation in a reactionary manner, with huge economic and environmental costs. Importantly, such a situation would have been difficult to avoid, because of the common 5 year planning horizon at which local level planning and management institutions operate, and the common mis-perception that climate change will be unidirectional. In the case of the Okavango Delta, the management plan formulated in 2006 is based on an unambiguously defined expectation of a progressively drier future climate (NCSA, 2008). Work such as that by Tyson et al. (2002) indicated the possibility of a wetter phase in the future. However, these results were circumstantial, and thus sidelined in the face of the "hard" evidence of the consistent decline in flood magnitudes observed since the 1970s, combined with acceptance of drying as an ultimate climate change outcome for the region. It is not surprising that the shift of the system to a wetter state was not foreseen and not planned for.

The need to adapt water management approaches to the lack of stationarity and presence of long periods characterized by different mean conditions has recently gained recognition (Milly et al., 2008). However, this alternative management framework remains to be developed for the Okavango.

From an ecological point of view, in the Okavango Delta multi-decadal oscillations affect plant successional processes operating at the time-scale of decades. These relate primarily to the relationship between herbaceous marsh vegetation and woody savannah vegetation. When multi-decadal oscillations head towards a dry period, in floodplains where flooding does not occur within 7 years, a successional trend towards savannah woodland begins (Heinl et al, 2004; Murray-Hudson, 2009). During the re-wetting limb of the multi-decadal cycle, there appear to be no ecological feedback mechanisms from the vegetation to the hydrology to prevent rapid reversion from woodland savannah to short life-cycle emergent marsh communities. This has been observed in the distal Okavango Delta during the hydrological years 2008/9 and 2009/10, in which extensive re-flooding of floodplains dry since the early 1980s, and colonised by *Acacia tortilis* woodland, was of sufficient duration and depth to result in a massive mortality of woody species. Clearly, such rapid switches from long to short life-cycle plant species have major influences on ecologically important processes like carbon sequestration and have repercussions on higher trophic levels affecting large herbivore populations, species composition and migration patterns. Given the open nature of the Okavango system, these changes will propagate into the larger regional socio-ecological sphere. From the ecological point of view, to accommodate multi-decadal oscillations without negative impacts on the integrity of the complex wetland ecosystem, the system should be managed at as large a geographic scale as possible; maintenance of a large open ecosystem confers the benefits of resilience, and keeps multiple options for socio-economic gain.

That the problems of multi-decadal oscillations are not only relevant to our study area is illustrated in Fig. 10. Large parts of southern Africa are characterized by multi-decadal rainfall differences of magnitude similar to, or larger than this observed in the Okavango. According to our results, the future of the Okavango is expected to be complex. Not only can one expect extended, multi-year periods of wetter and drier conditions, but importantly, the wetter are expected to be progressively less wet, and the drier to be progressively more dry. Without detailed targeted analyses, these results cannot be extrapolated to other areas in southern Africa or elsewhere that display long-term climate oscillations. We can only hypothesize that similar effects might occur in other catchments. Even so, it is evident that where these multi-decadal oscillations are present, successful adaptation strategies will need to allow and plan for such changes.

5 Acknowledgements

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Figure captions

Fig. 1 Main features of the Okavango system, showing zoning used in analyses.

Fig. 2. 30-year running averages of (a) Rainfall at Maun (P_{MAUN} obs) and area-averaged CRU rainfall over zones 1-3 (P_{CRU} zone 1-3), (b) Area-averaged PET derived over zones 1-3 from CRU temperatures (PET_{CRU}), (c) Okavango River discharges at Mohembo from observations (Q_{OKA} obs) and simulations from four idealized sensitivity runs (Q_{OKA} run 1-4), (d) Thamalakane River discharges at Maun from observations (Q_{THA} obs) and simulations from four idealized sensitivity runs (Q_{THA} run 1-4) (e) NAO and PDO indices. Note that in all cases the 30-year running mean in each year is calculated from the years preceding that year (not centred on that year).

Fig. 3 MTM spectra of: observed rainfall at Maun (P_{MAUN}), CRU rainfall for zones 1-3 (P_{CRU}) and PET based on CRU temperatures for zones 1-3 (PET_{CRU}).

Fig. 4 MTM spectra of: Okavango River discharges at Mohembo, observed (Q_{OKA} obs), simulated under 4 idealized sensitivity runs (Q_{OKA} run 1-4) and Thamalakane

River at Maun: observed (Q_{THA} obs) and simulated under 4 idealized sensitivity runs (Q_{THA} run 1-4). Solid line – MTM periodogram, dashed line – 0.1 significance level.

Fig. 5 30-year running averages of rainfall (P) and PET in zone 1 of the Okavango region, observed (from CRU) and in 40 members of GCM MME.

Fig. 6 Anomalies of 30-year running averages of rainfall for 40-member GCM MME, and P_{CRU}. Anomalies calculated with respect to 1935-2000 mean.

Fig. 7 Anomalies of 30-year running averages of the Okavango River discharges at Mohembo (Q_{OKA}) simulated with CRU and 40-member GCM MME data. Anomalies calculated with respect to 1935-2000 mean.

Fig. 8 30-year running averages of the Okavango River discharges at Mohembo (Q_{OKA}), and Thamalakane River at Maun (Q_{THA}) simulated with CRU and 40-member GCM MME data.

Fig. 9 Average spectral power of 30-60 year quasi-periodicities in the Okavango River discharges at Mohembo simulated with MME GCM climates for 1935-2000 (past) and 2035-2100 (future).

Fig. 10 Peak-to-trough range of 30-year running mean as a percentage of the mean rainfall from CRU data

Table 1 Descriptive statistics of analysed data sets

Variable	Unit	Average (entire record)	Range of 30-year running mean	Range as % of average
P_{MAUN}	mm $year^{-1}$	450	118	26.2
P_{CRU}	mm $year^{-1}$			
zone 1		476	73	15.3
zone 2		652	73	11.2
zone 3		1024	82	8.0
PET_{CRU}	mm $year^{-1}$			
zone 1		1600	57	3.5
zone 2		1609	29	1.8
zone 3		1424	29	2.0
Q_{OKA}obs	$Mm^3 year^{-1}$	9200	2628	28.5
Q_{OKA}	$Mm^3 year^{-1}$			
run 1		9324	1652	17.7
run 2		8836	722	8.2
run 3		9455	1426	15.1
run 4		8648	891	10.3
Q_{THA}obs	$Mm^3 year^{-1}$	235	391	79
Q_{THA}	$Mm^3 year^{-1}$			
run 1		218	237	108.7
run 2		125	81	64.8

run 3	212	193	91.0
run 4	106	60	56.6

Figure1

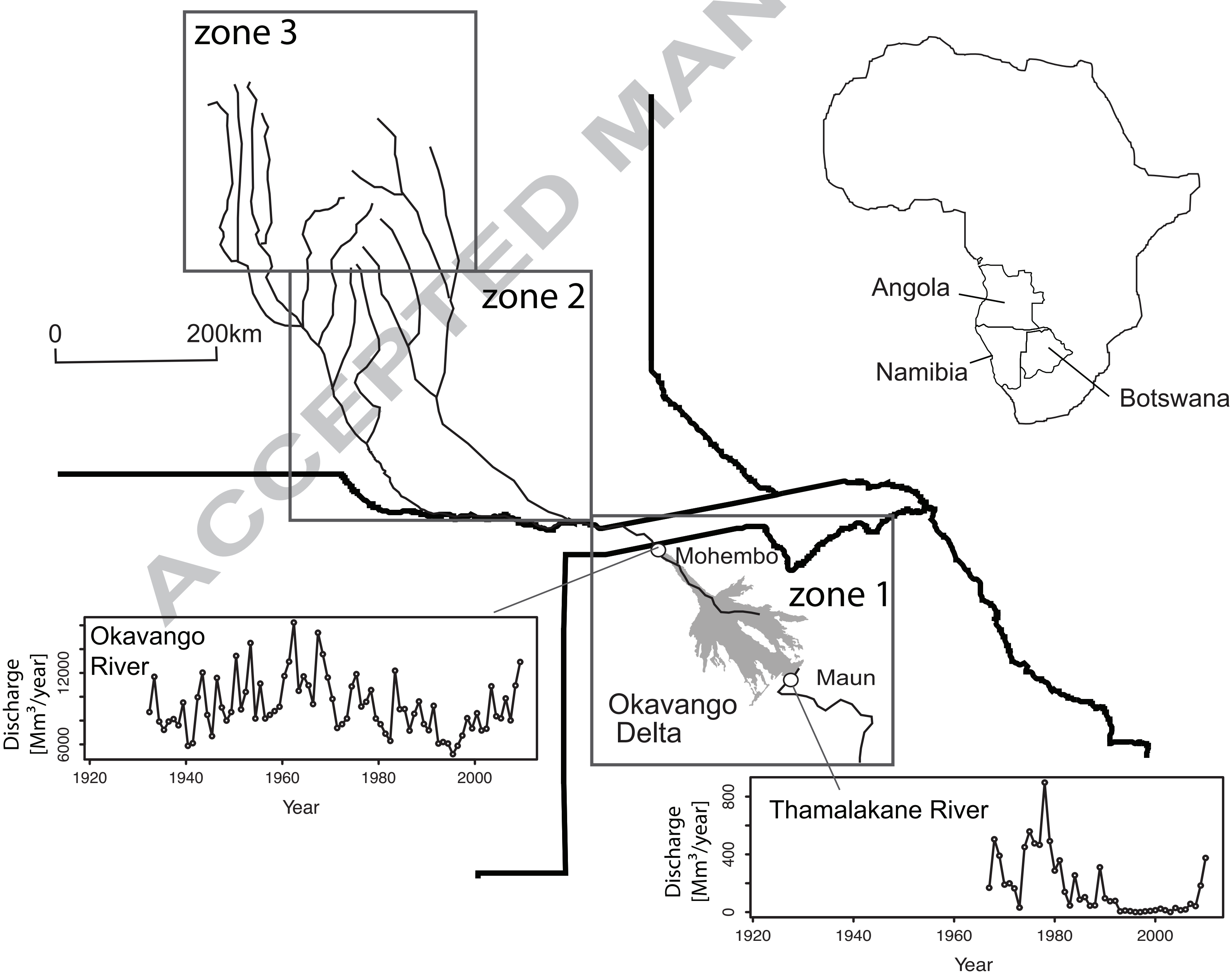
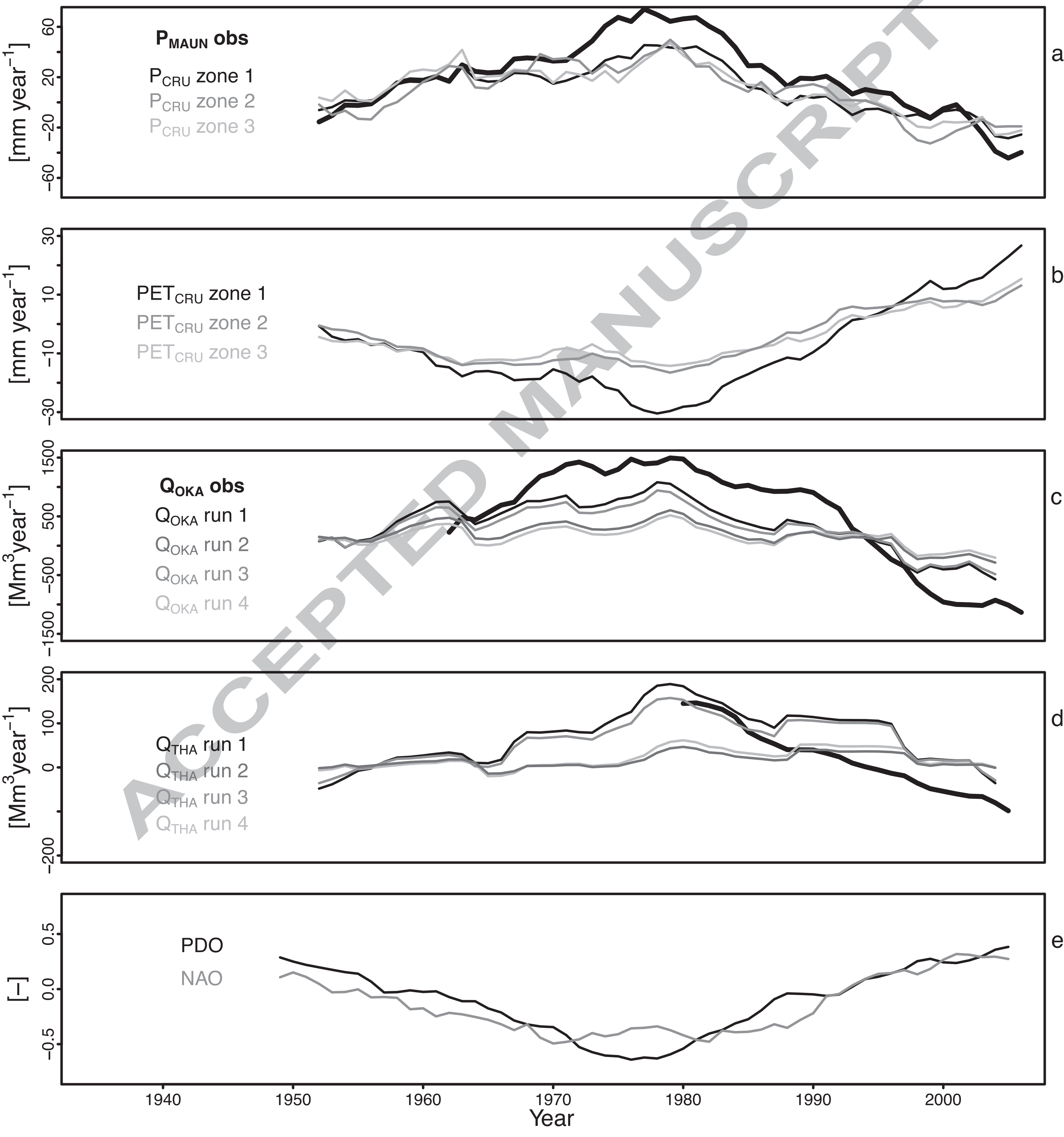
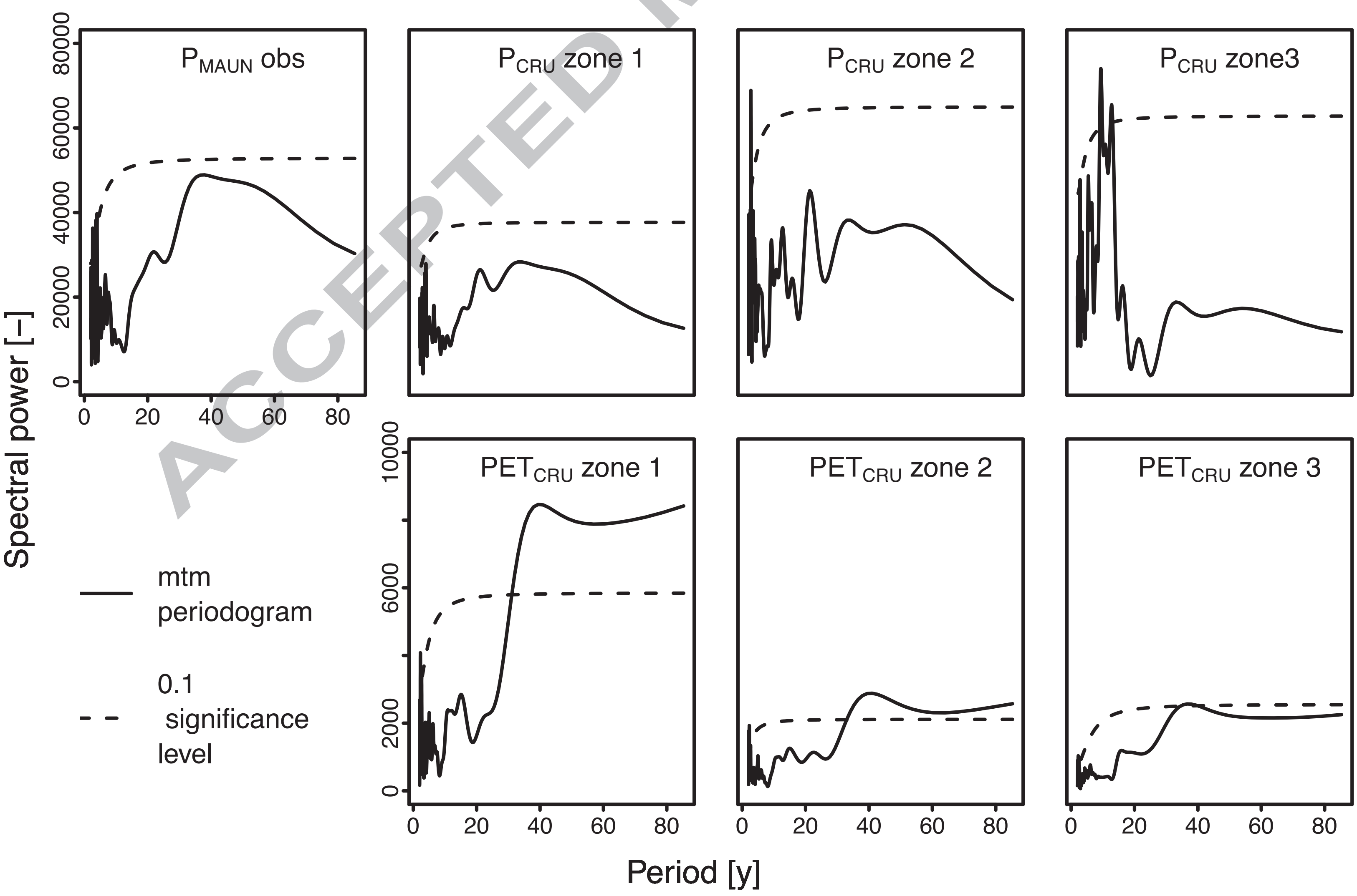

zone 3
zone 2
zone 1
0
200km
Angola
Namibia
Botswana
Mohembo
Maun
Okavango Delta
Okavango River
Discharge [Mm^3/year]
12000
6000
1920
1940
1960
1980
2000
Year
Thamalakane River
Discharge [Mm^3/year]
800
400
0
1920
1940
1960
1980
2000
Year

Figure2



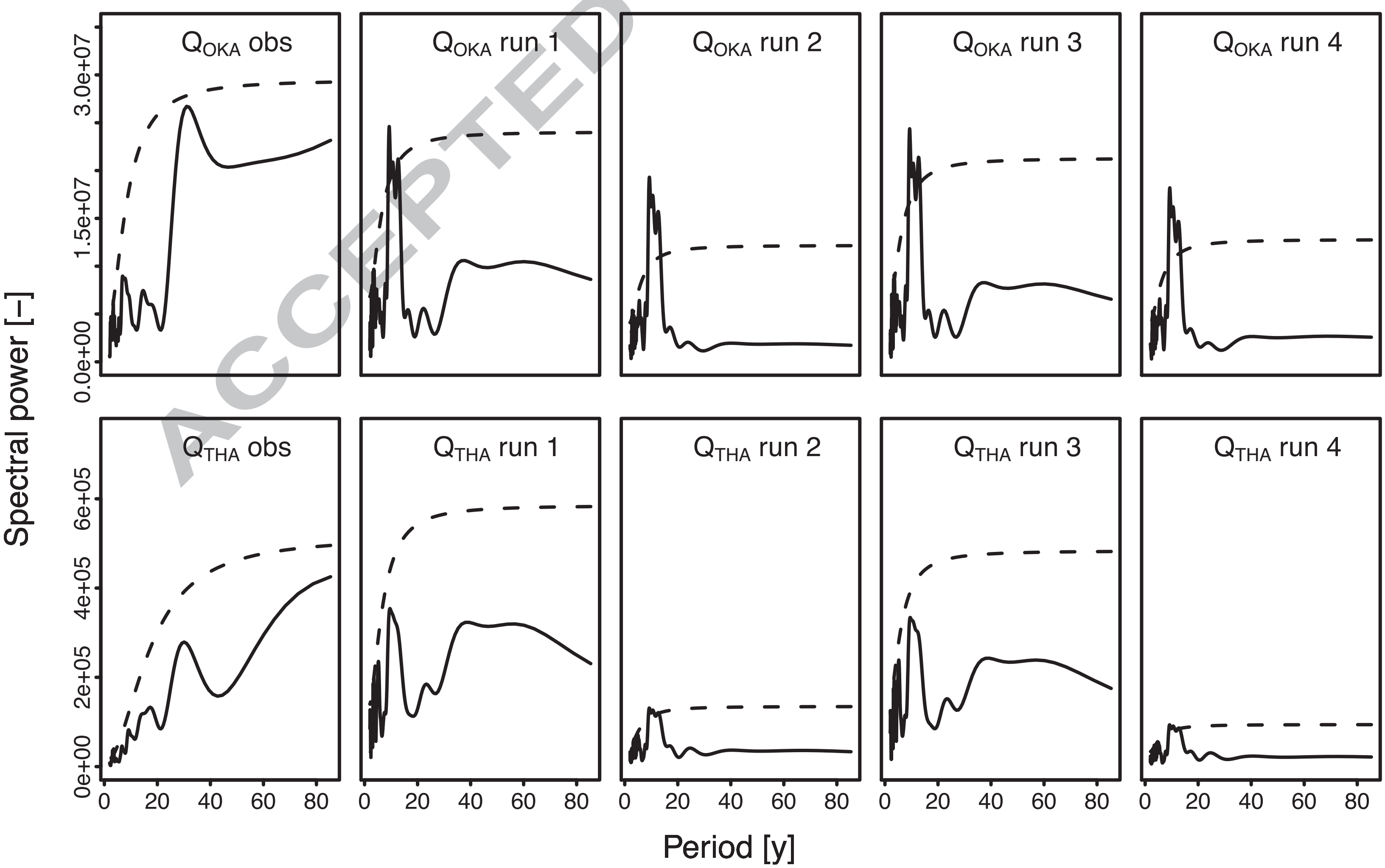
P_MAUN obs
P_CRU zone 1
P_CRU zone 2
P_CRU zone 3
[mm year^-1]
60
20
-20
-60
a
PET_CRU zone 1
PET_CRU zone 2
PET_CRU zone 3
[mm year^-1]
30
10
-10
-30
b
Q_OKA obs
Q_OKA run 1
Q_OKA run 2
Q_OKA run 3
Q_OKA run 4
[Mm^3year^-1]
1500
500
-500
-1500
c
Q_THA run 1
Q_THA run 2
Q_THA run 3
Q_THA run 4
[Mm^3year^-1]
200
100
0
-200
d
PDO
NAO
[-]
0.5
0.0
-0.5
e
1940
1950
1960
1970
1980
1990
2000
Year

Figure3



P_MAUN obs
P_CRU zone 1
P_CRU zone 2
P_CRU zone3
PET_CRU zone 1
PET_CRU zone 2
PET_CRU zone 3
Spectral power [–]
Period [y]
0
20000
40000
60000
80000
2000
6000
10000
20
40
60
80
mtm periodogram
0.1 significance level

Figure4



Q_{OKA} obs
Q_{OKA} run 1
Q_{OKA} run 2
Q_{OKA} run 3
Q_{OKA} run 4
Q_{THA} obs
Q_{THA} run 1
Q_{THA} run 2
Q_{THA} run 3
Q_{THA} run 4
0.0e+00
1.5e+07
3.0e+07
0e+00
2e+05
4e+05
6e+05
0
20
40
60
80
Spectral power [–]
Period [y]

Figure5

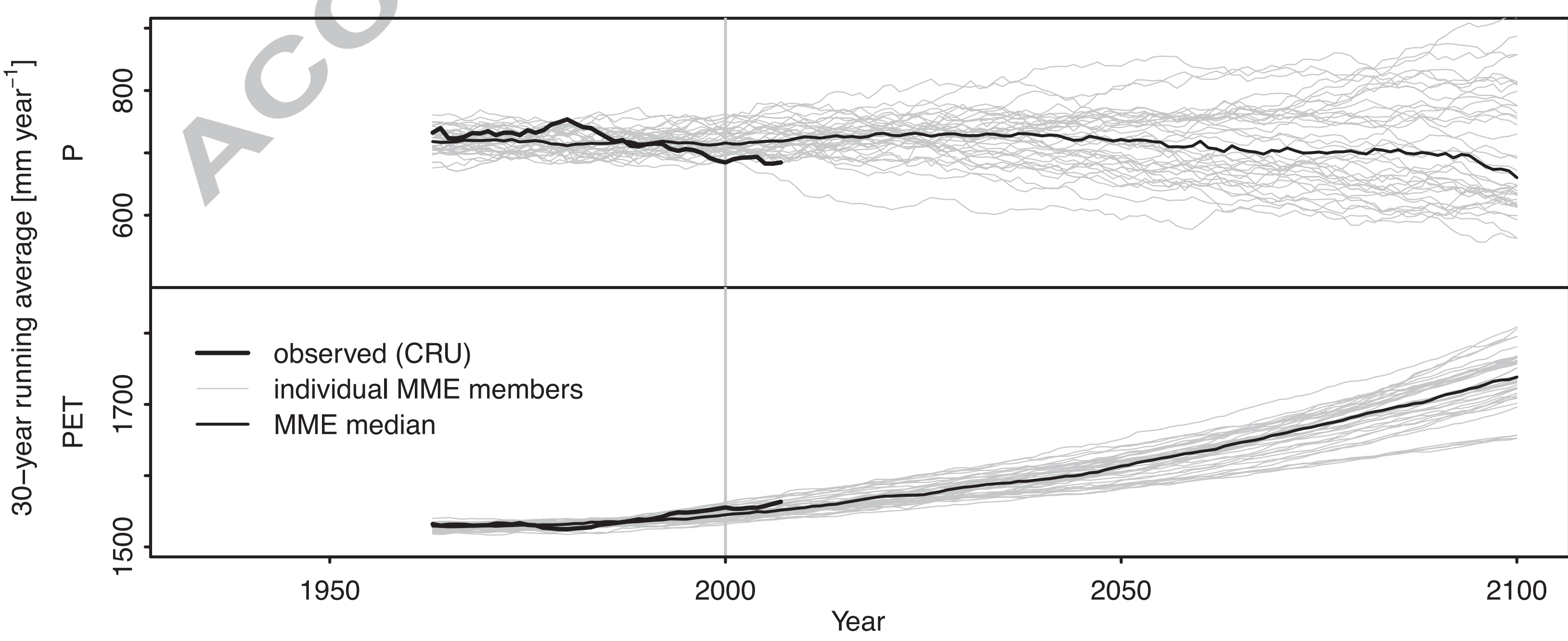

30−year running average [mm year^{-1}]
P
800
600
PET
1700
1500
observed (CRU)
individual MME members
MME median
1950
2000
2050
2100
Year

Figure6

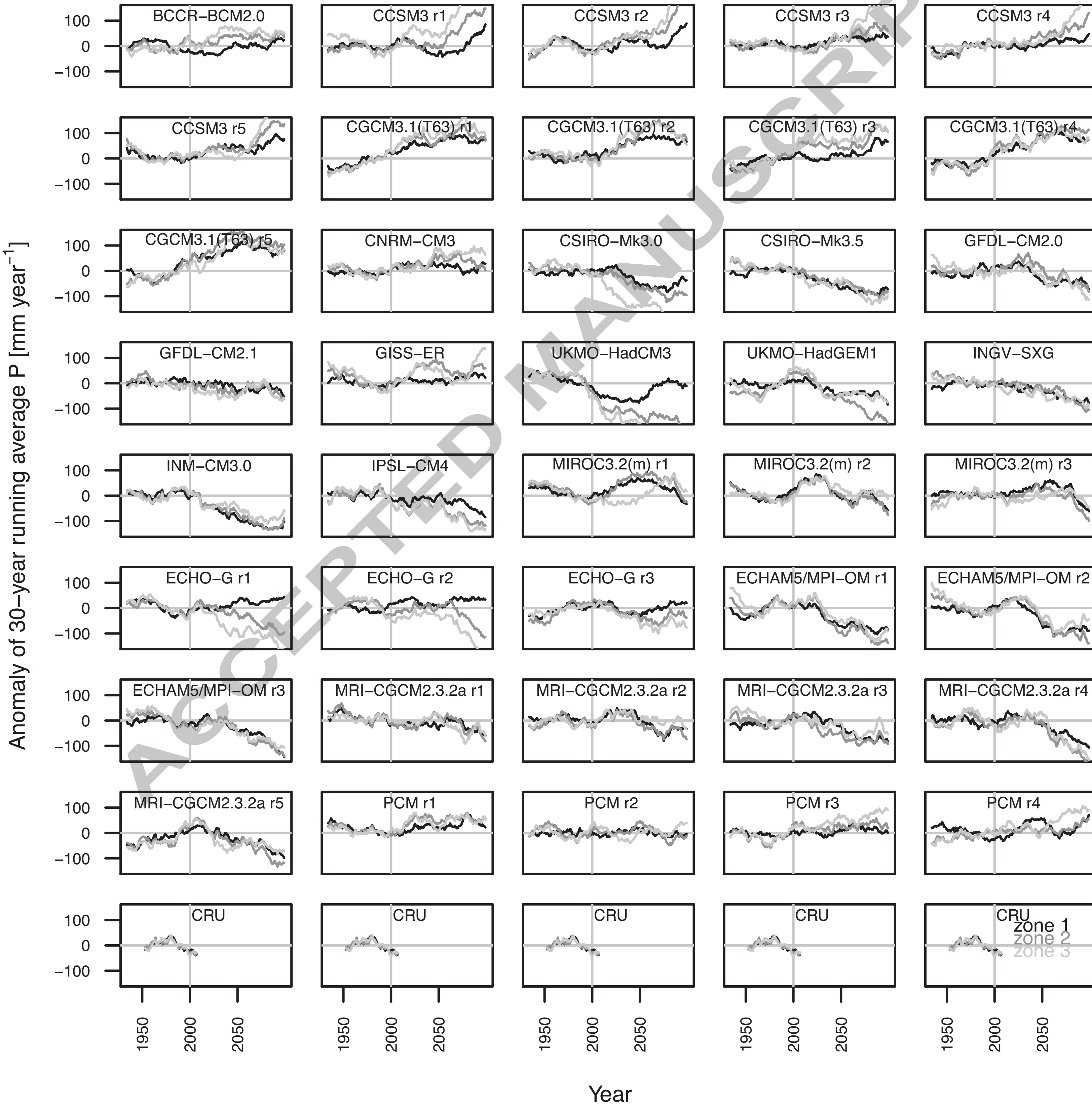
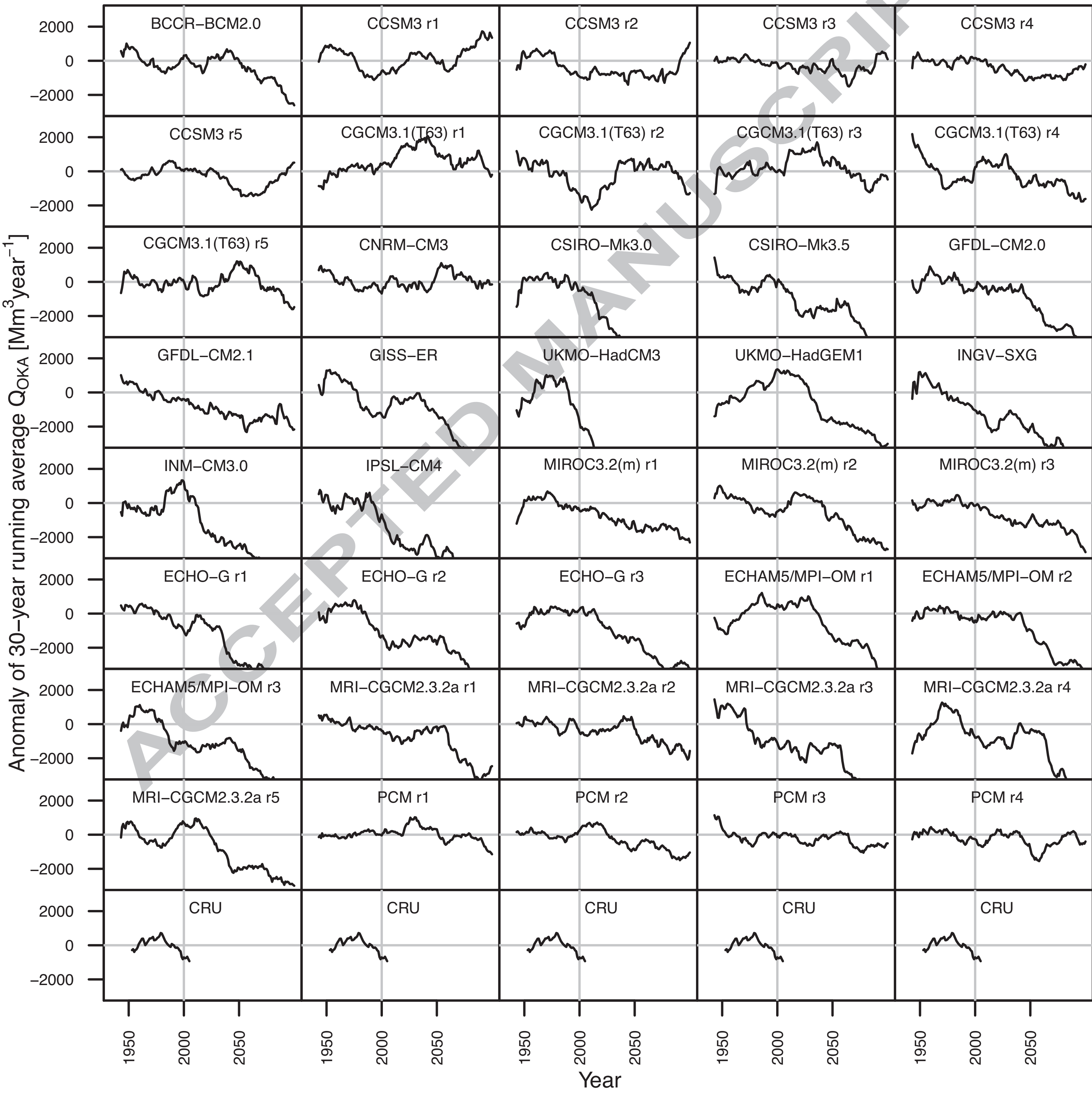

BCCR−BCM2.0
CCSM3 r1
CCSM3 r2
CCSM3 r3
CCSM3 r4
CCSM3 r5
CGCM3.1(T63) r1
CGCM3.1(T63) r2
CGCM3.1(T63) r3
CGCM3.1(T63) r4
CGCM3.1(T63) r5
CNRM−CM3
CSIRO−Mk3.0
CSIRO−Mk3.5
GFDL−CM2.0
GFDL−CM2.1
GISS−ER
UKMO−HadCM3
UKMO−HadGEM1
INGV−SXG
INM−CM3.0
IPSL−CM4
MIROC3.2(m) r1
MIROC3.2(m) r2
MIROC3.2(m) r3
ECHO−G r1
ECHO−G r2
ECHO−G r3
ECHAM5/MPI−OM r1
ECHAM5/MPI−OM r2
ECHAM5/MPI−OM r3
MRI−CGCM2.3.2a r1
MRI−CGCM2.3.2a r2
MRI−CGCM2.3.2a r3
MRI−CGCM2.3.2a r4
MRI−CGCM2.3.2a r5
PCM r1
PCM r2
PCM r3
PCM r4
CRU
zone 1
zone 2
zone 3
100
0
−100
1950
2000
2050
Anomaly of 30−year running average P [mm year−1]
Year

Figure7



BCCR−BCM2.0
CCSM3 r1
CCSM3 r2
CCSM3 r3
CCSM3 r4
CCSM3 r5
CGCM3.1(T63) r1
CGCM3.1(T63) r2
CGCM3.1(T63) r3
CGCM3.1(T63) r4
CGCM3.1(T63) r5
CNRM−CM3
CSIRO−Mk3.0
CSIRO−Mk3.5
GFDL−CM2.0
GFDL−CM2.1
GISS−ER
UKMO−HadCM3
UKMO−HadGEM1
INGV−SXG
INM−CM3.0
IPSL−CM4
MIROC3.2(m) r1
MIROC3.2(m) r2
MIROC3.2(m) r3
ECHO−G r1
ECHO−G r2
ECHO−G r3
ECHAM5/MPI−OM r1
ECHAM5/MPI−OM r2
ECHAM5/MPI−OM r3
MRI−CGCM2.3.2a r1
MRI−CGCM2.3.2a r2
MRI−CGCM2.3.2a r3
MRI−CGCM2.3.2a r4
MRI−CGCM2.3.2a r5
PCM r1
PCM r2
PCM r3
PCM r4
CRU
2000
0
−2000
1950
2000
2050
Anomaly of 30−year running average Q_{OKA} [$Mm^3 year^{-1}$]
Year

Figure8

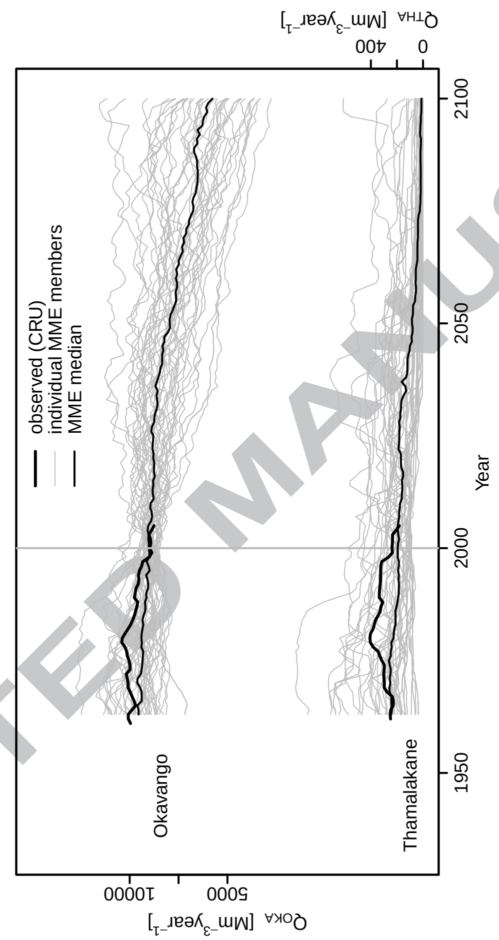
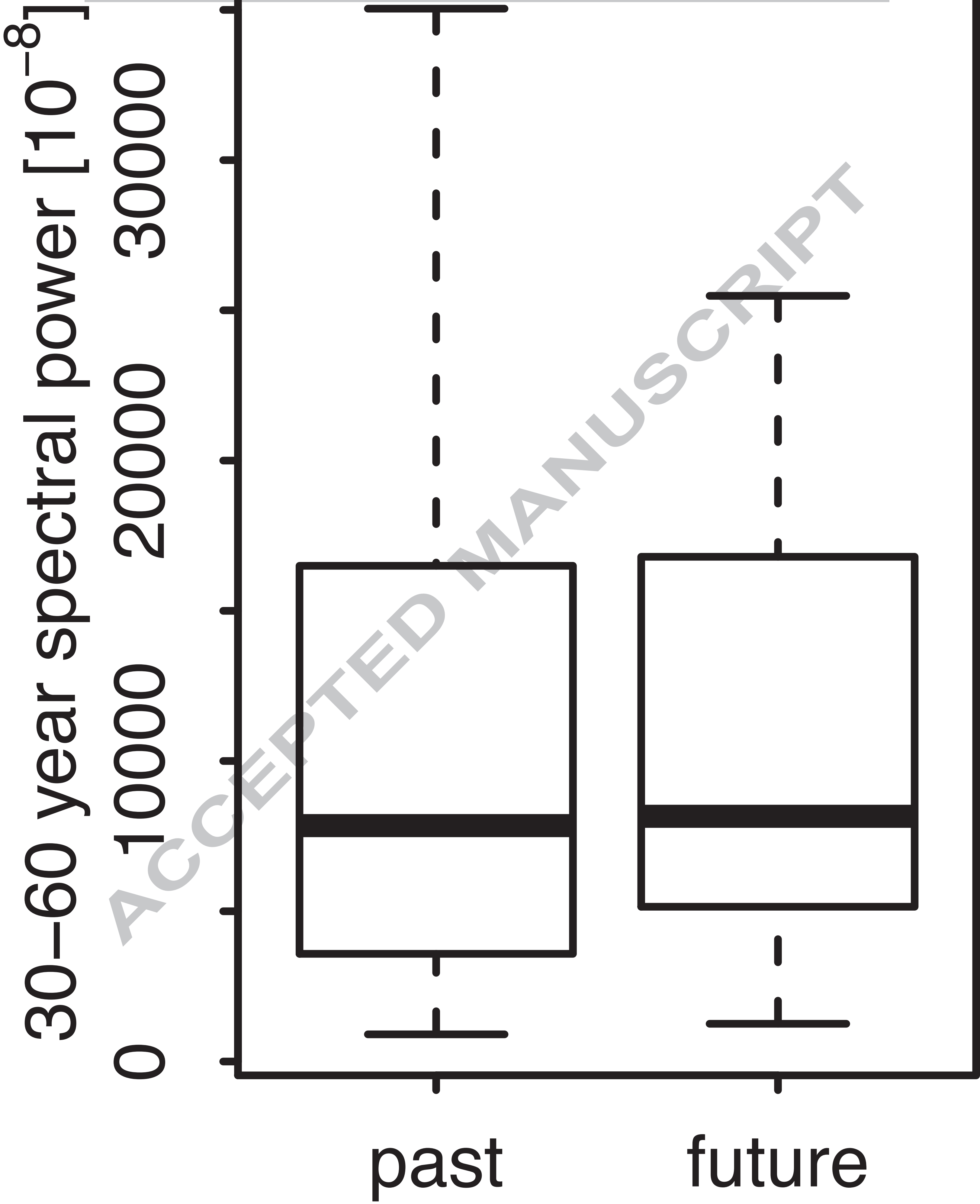
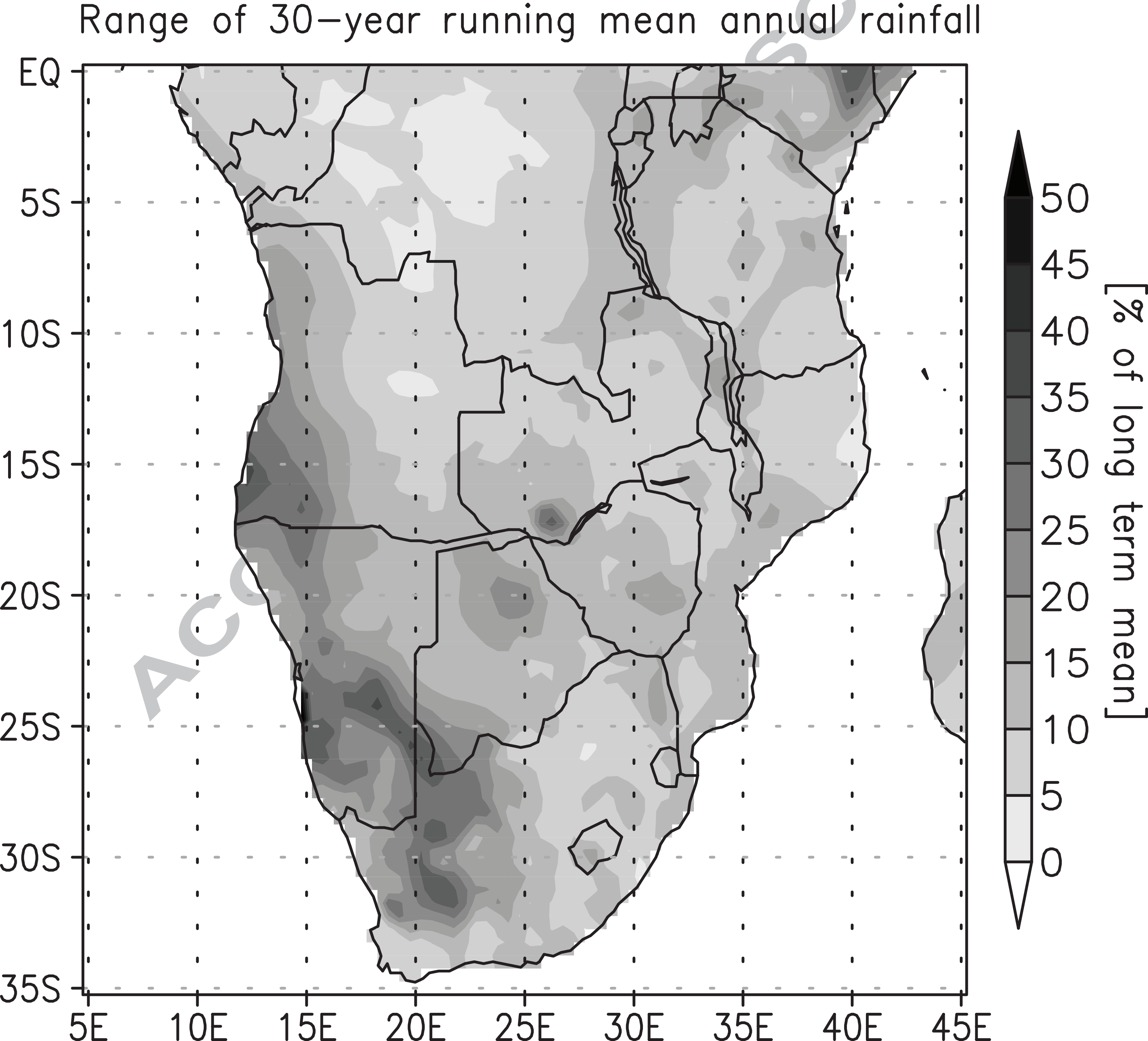

observed (CRU)
individual MME members
MME median
Okavango
Thamalakane
Year
1950
2000
2050
2100
Q_{OKA} [Mm^{-3}year^{-1}]
5000
10000
Q_{THA} [Mm^{-3}year^{-1}]
0
400

Figure9



30–60 year spectral power [10^{-8}]
0
100000
200000
300000
past
future

Figure10


Range of 30-year running mean annual rainfall
EQ
5S
10S
15S
20S
25S
30S
35S
5E
10E
15E
20E
25E
30E
35E
40E
45E
50
45
40
35
30
25
20
15
10
5
0
[% of long term mean]

>Multi-decadal oscillations in the Okavango River basin, southwestern Africa
>Weak multi-decadal rainfall signal magnified by catchment processes
>GCMs simulate multi-decadal oscillations in 20th century
>Oscillations in 21st century similar in magnitude but superimposed on drying trend
>Multi-decadal oscillations affect climate change assessments and require alternative water management approaches